3

Ice Age Cycles

3.1 The Astronomical Theory of Climate Change

Back in 1830, when Lyell was writing volume 1 of his *Principles*, he knew that glaciers had advanced and retreated. That led him to wonder if significant changes in our climate through time might be driven by some regular astronomical control on the amount of sunlight Earth received. To address this question, Lyell turned to his friend, the English astronomer John Herschel (1792–1871), another Fellow of the Royal Society, knighted in 1831. Herschel explained that the amount of sunlight falling anywhere on the Earth's surface varies with regular changes in the 'eccentricity' of the Earth's orbit around the Sun, in the 'precession of the equinoxes' and in the tilt (or 'obliquity') of the Earth's axis.

Starting with eccentricity, it seems self-evident that if Earth were the only planet orbiting the Sun, it would follow a circular orbit. But it is not and does not. Earth's orbit is influenced by the gravitational pull of its giant sister planets, which converts our orbit into an ellipse with the Sun off-centre, a state called 'eccentric'. The eccentricity of the Earth's orbit slowly changes from more or less circular, or 'centric' (with the Sun at the centre), to 'eccentric' and back following cycles of about 400 and 100 Ka. That affects climate, because when the orbit is at its most elliptical, the amount of radiation the Earth gets from the Sun at perihelion (the point on the orbit closest to the Sun) is 23% more than it gets at aphelion (the point on the orbit furthest from the Sun).

The way in which that radiation is distributed over the planet depends on the fact that the position of the Earth at any given point in time (e.g. the spring equinox (time of equal hours of day and night) in March) migrates slowly around the Earth's orbit in a cycle lasting about 21 Ka, known as the 'precession of the equinoxes' (for more details, see Appendix 1 of Reference 1). This migration has little effect on the climate when the Earth's orbit is more or less circular, but a large effect when the orbit is eccentric. Currently, the Earth is closest to the sun (at perihelion) in mid-winter, making Northern Hemisphere winters warm. In about 10.5 Ka, Earth will be furthest from the sun (at aphelion) in mid-winter, making Northern Hemisphere winters cool. The Earth's orbit is currently close to circular, so these differences have little effect at present. The effect will increase as the orbit becomes more eccentric with time. The effects of precession are greatest in the tropics.

Most people know that the Earth's spin axis is tilted at an angle of around 23° to the plane of the Earth's orbit, which accounts for the seasons. If the axis were upright, we would still have climatic zones – with more heat at the Equator and less at the poles – but no seasons. The tilt of the axis fluctuates from around 21.5° to around 24.5° and back on a cycle of 40 Ka. The higher the angle, the more the seasonal difference, with summers receiving more energy from the Sun, and winters less. The effects of the tilt cycle are greatest in temperate and polar latitudes, where snow accumulates when tilt is high and winters are cold.

Interaction between these three cycles controls the amount of **in**coming **sol**ar radi**ation – 'insolation'** – received at any point on the Earth's surface through time. These cycles are so regular that astronomers can use them to calculate the amount of insolation anywhere on the Earth's surface over periods of millions of years.

Earth's Climate Evolution, First Edition. Colin P. Summerhayes.

The Sun being the major driver of Earth's climate, these calculations provide geologists with a first-order means of estimating climate change.

Herschel presented his ideas on the astronomical theory of climate change to the Geological Society in December 1830[2]. He speculated that extreme variations in the eccentricity of the Earth's orbit might exaggerate the difference between summer and winter temperature, and that these might combine with the effect of precession of the equinoxes to produce '*periodical fluctuations in the quantity of solar heat received by the earth, every such fluctuation being of course accompanied with a corresponding alteration of climates; and therefore, if sufficiently extensive and continued, giving room for variation in the animal and vegetable productions of the same region at different and widely remote epochs.*' Herschel thought that the variation in the tilt of the Earth's axis was insufficient to affect the climate. He regarded '*the excentricity [sic] as the only element whose variation can possibly have any effect of the kind in view.*' He went on to say, '*by reason of the precession of the equinoxes combined with the motion of the apogee of the earth's orbit, the two hemispheres would alternately be placed in climates of a very opposite nature, the one approaching a perpetual spring, the other to extreme vicissitudes of a burning summer and a rigorous winter.*' Obscure prose indeed, but I'm sure you get the drift. Observing that the Earth's orbit was becoming more centric, he thought that this might indicate a cooling. We have to remember that these were early days and that Herschel was arguing without the benefit of detailed calculations of orbital changes, although they could have been determined from the work of the great French astronomer, Laplace.

Based on his discussions with Herschel, Lyell observed in volume 1 of *Principles* that it is '*of importance to the geologist to bear in mind that in consequence of the precession of the equinoxes, the two hemispheres receive alternately, each for a period of upwards of 10 000 years, a greater share of solar light and heat. This cause may sometimes tend to counterbalance inequalities resulting from other circumstances of a far more influential nature; but, on the other hand, it must sometimes tend to increase the extremes of deviation, which certain combinations of causes produce at distant epochs*'[2]. This dense prose hid the fact that Lyell suspected that these astronomical changes might affect climate enough to be detectable in the geological record, but had no idea if this were the case.

At the time, in 1830, Agassiz had not yet 'discovered' the Ice Age. The honour of being the first to conclude that astronomical forces controlled what happened during the Ice Age thus goes to French mathematician Joseph Alphonse Adhémar (1797–1862), who had the brilliant intuition that Agassiz's glaciations must be periodic and thus controlled by celestial mechanics, publishing his ideas in 1842[4]. He calculated that periods of cooling and warming would correspond to the 21 Ka precession cycle, and that they would alternate between the two hemispheres.

3.2 James Croll Develops the Theory

The first scientist to investigate the astronomical theory of climate change in detail was Scottish physicist-cum-geologist James Croll (1821–1890) (Figure 3.1, Box 3.1), the man who disagreed with Lyell's ideas about boulder clay.

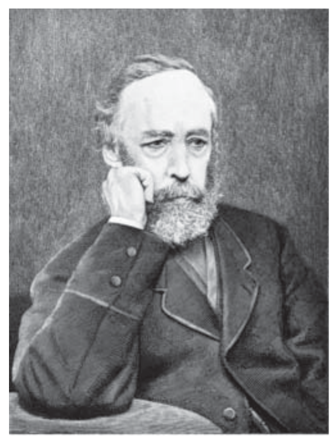

Figure 3.1 *James Croll.*

Box 3.1 James Croll.

Croll's scientific career began late in life. Born on a farm near Wolfhill in Perthshire, Scotland in 1821, he was largely self-educated in mathematics and astronomy. Leaving school at age 13, he worked as a millwright, a carpenter, a tea merchant, the keeper of a temperance hotel, a life-insurance salesman and a writer for a temperance newspaper, before becoming caretaker of the museum at Anderson

College in Glasgow in 1859, at the age of 38. That gave him access to a fine scientific library, exposing him to the work of Herschel and Adhémar and enabling him to develop his own ideas about one of the 'hot' topics of the era: the origin of the Ice Age. His findings led to him being invited to work at the Geological Survey of Scotland, which he did from 1867 to 1881. For his Ice Age research, he was elected a Fellow of the Royal Society in 1876 and awarded an Honorary Degree by the University of St Andrews. He retired due to ill health in 1880 and died in 1890. The Quaternary Research Association now awards the James Croll Medal.

Thinking about the Ice Age, Croll felt sure that '*The recurrence of colder and warmer periods evidently points to some great, fixed, and continuously operating cosmic law*'[5]. Immersing himself in the studies of celestial mechanics by Frenchmen Pierre Simon de Laplace and Urbain Leverrier, discoverer of the planet Neptune, he worked out a more complex theory to explain the effect of seasonal contrasts of insolation, publishing his results in 1864[5]. His paper refined predictions of the timing of the glacial epochs of the Ice Age and showed how changes in the Earth's orbit provided a periodic extraterrestrial mechanism for initiating *multiple* glacial epochs. These would occur every 22 Ka, and when there was a glacial period in the north, there would be an interglacial in the south, as suggested by Adhémar. Unlike Adhémar, Croll thought that eccentricity was important, because the accumulation of snow would be encouraged by decreased sunlight and longer winters when the orbit was most elliptical and the Earth was furthest from the sun (at aphelion).

One of the most important and overlooked aspects of Croll's analysis of the astronomical theory of climate change was his realisation that the change in heat received by the Earth due to orbital changes was *not enough by itself* to cause glaciation. He concluded correctly that '*glacial cycles may not arise directly from cosmical causes, they may do so indirectly!*'[6] Feedbacks were needed. The effect of decreased insolation was amplified by increasing accumulation of snow and ice, which increased the reflectiveness of the Earth's surface – its albedo. This increased the development of mists and fogs, reflecting yet more solar energy.

Croll also considered how changes in insolation would affect winds and ocean currents[5]. Cooling of the poles in glacial periods would steepen the thermal gradient in the air between pole and Equator, making winds stronger. Glaciation in the Northern Hemisphere would weaken the Gulf Stream, which carried warm water from the Equator to the Arctic. It would also strengthen the Northeast Trade Winds, which would force the Equatorial Current south, limiting the supply of warm water to the Gulf Stream from the South Atlantic; '*The Gulf-stream would consequently be greatly diminished, if not altogether stopped*'[5]. If that were so, he speculated that the climate of northern Europe would resemble that of Greenland[7]. This is more or less what occurred during the Ice Age.

Lyell was intrigued, and began corresponding with Croll. This interaction led to Croll being appointed in 1867 to a clerical position as keeper of maps and correspondence in the Geological Survey of Scotland, where the director, Sir Archibald Geikie, encouraged his research. In 1875, Croll summarised his research findings in an influential book, *Climate and Time*[7] (Figure 3.2).

Given the importance he attached to the decrease of heat from the Gulf Stream as one of the positive feedbacks enhancing the glaciation of the north, Croll was keen to find out more about the nature of ocean circulation, then a topic of much speculation[8]. He closely monitored the work of physiologist William Carpenter (1813–1885), a scientist keen to test the notion of Edward Forbes (1815–1854) that there was no life in the deep ocean – it was 'azoic'. As registrar of the University of London and vice-president of the Royal Society, Carpenter used his influence to access a Royal Navy ship, HMS *Porcupine*, which, in 1870, dredged numerous creatures from the deep sea and so killed off Forbes's azoic theory.

Carpenter's work with the *Porcupine* showed most of the deep North Atlantic to be extremely cold. He thought this meant that a deep current originating in the Arctic carried cold water south into the interior of the Atlantic, and '*embarked on the development of his "magnificent generalization" that the cold temperatures were part of a large-scale general ocean circulation*'[8]. In his conceptual model, this deep current replaces the warmer surface water that flows from the Equator towards the poles. He saw '*this flow of water toward the equator and its eventual return towards the pole [as] just as much a physical necessity as that interchange of air which has so large a part in the production of winds*'[8]. Density was an important driver in Carpenter's model of the general circulation, with lighter, warmer water at the surface moving north connected to denser, colder water at depth moving south and eventually returning to the surface near the Equator. These were important insights into ocean circulation, which helps to

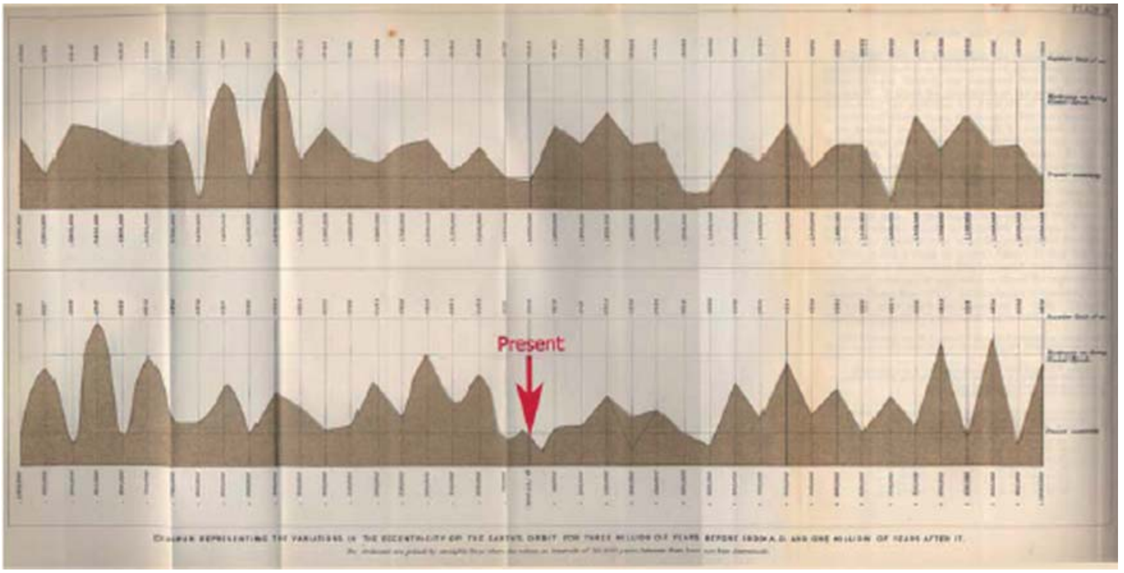

Figure 3.2 *Croll's orbital variations. Variations in the earth's orbit for 3 Ma before 1800 AD and 1 Ma thereafter. Each division on the horizontal axis represents 50,000 years. Croll thought that when the orbit was most eccentric (i.e. elliptical, with high values along the vertical axis) there would be longer winters allowing more snow to accumulate. In contrast, low values of eccentricity would equate with warm climates. The arrow indicating 'present' conditions denotes the position of 1800 AD, when eccentricity was close to its lowest value.*

regulate Earth's climate, although we now know that the return to surface takes place around Antarctica, not at the Equator.

Croll disagreed with Carpenter's model, setting out his own conception of how ocean currents contributed to glaciations[7,8]. There just wasn't enough oceanographic information to enable them to resolve their differences, however[8]. The controversy did have one happy outcome, in providing a *raison d'être* for the world-encircling oceanographic expedition of HMS *Challenger* in 1872–76, which would create a much clearer picture of ocean circulation than was available to either man.

Although Croll focused his attention on precession and eccentricity, he suspected that changes in the tilt of the Earth's axis might also affect the climate, especially at the poles, where the longer summers at times of maximum tilt would melt more snow and ice than at other times. He surmised that particular combinations of eccentricity, precession and axial tilt would lead to periods of ice melt that would raise sea level, and that oscillations of sea level should be associated with changes from interglacial to glacial conditions – another prescient conclusion. Lacking calculations of the changes in tilt through time, Croll could do little more than speculate about their effects. We now know that changes in axial tilt do have a strong effect in the polar regions. Croll was on the right track, and that got geologists thinking in the right direction. Noting that tilt was at a maximum 11.7 Ka ago, he speculated that this might have led to a rise in sea level that would explain the occurrence of raised beaches from about that period in Scotland and Scandinavia. This was a perceptive observation, although it ignored the effect of the isostatic upward adjustment of the land in response to the removal of the last ice sheet.

Croll was also one of the first to note the occurrence beneath the Scottish boulder clay of buried river channels, the depths of whose beds showed that they must have been cut when sea level was much lower. The cutting of deep channels implied that the sea level had dropped, thus steepening the gradient of the rivers' beds. While Croll thought the channels might have been cut during warm periods, it seems more likely that they were cut when ice sheets were extensive and sea level was low, both as the climate was cooling and as it was warming. Channel cutting would cease when the ice sheets advanced to the edge of the continental shelf.

In one particularly perceptive leap of the imagination, Croll deduced[7] that '*If the glacial epoch resulted from a high condition of eccentricity, we have not only a means of determining the positive date of that epoch, but we also have a means of determining geological time in absolute measure.*' This turned out to be the case, although not in precisely the way Croll imagined, as we shall see later. Following this leap to its logical conclusion, he calculated eccentricity not only for 3 Ma into the past, but also for 1 Ma into the future (Figure 3.2), making him the first to take a mathematical approach to estimating future climate change.

3.3 Lyell Responds

Having read Croll's 1864 paper[5] and corresponded with him, Lyell modified the last three editions of his *Principles of Geology* (numbers 10 in 1866, 11 in 1872 and 12 in 1875) to introduce a new chapter, 13, on 'Vicissitudes in Climate – How Far Influenced by Astronomical Changes'[9–11]. It explained how changes in the eccentricity of the Earth's orbit in combination with the precession of the equinoxes would cause alternations of climate with a period of around 21 Ka, repeated thousands of times throughout the geological past, which might explain '*some of the indications of widely different climates in former times*'[11]. Lyell attributed to Croll the observation that winters would be at their coldest when the Earth was at aphelion (farthest from the sun) and the orbit was at its most eccentric. The development of large amounts of ice at those times, Lyell went on to note, '*must have given rise at certain periods to some differences in the ocean's level*'[11]. This is a rather late acknowledgment of the notion that ice ages might be times of lowered sea level, which Charles Maclaren had proposed as early as 1842[12].

Despite the attractive features of the astronomical theory of climate change, Lyell thought that Croll had given insufficient credence to Lyell's own principle that '*abnormal geographical conditions*' – meaning the existence of land near or over the poles – were '*far the most influential in the production of great cold*'[11]. He reminded his readers that '*The simple fact that totally different climates exist now in the same hemisphere and under the same latitude would alone suffice to prove that their occurrence cannot be exclusively due to astronomical influence*'. For example, '*the climates of South Georgia and Tierra del Fuego are at present so different that the former might be supposed to belong to a glacial period, while the latter, by its flowers and humming-birds in the winter, and the genera of marine molluscs in the adjoining sea, might indicate to the traveller, as well as to some future geologist, such a temperature as has been spoken of as perpetual spring. This contrast is due to geographical causes.*' The confusion in Lyell's mind arose because the movements of continents, which could indeed cause changes in climate, took place on a time scale of millions of years, while the variations of the astronomical theory were measured in tens or hundreds of thousands of years.

Although Lyell considered '*the former changes of climate and the quantity of ice now stored up in polar latitudes to have been governed chiefly by geographical conditions*', he accepted that the combination of a large excess of polar land with maximum eccentricity of the Earth's orbit '*would produce an exaggeration of cold in both hemispheres*'[11]. To see when maximum eccentricity occurred, he had colleagues draw up a table showing the eccentricity of the Earth's orbit over the last 1 Ma. The table, on page 285 of the 12th edition of *Principles*, shows that major eccentricity occurred at intervals of about 100 Ka, more or less in agreement with modern calculations, with the greatest eccentricity within relatively recent times occurring some 200–210 Ka ago[11].

Changes in the tilt of the Earth's axis, Lyell agreed[11], might also have some effect on the climate, greater tilt causing colder winters at the poles. If that condition were combined with maximum eccentricity and abundant polar land, '*this would favour a glacial epoch*'[11].

Despite their differences, Croll and Lyell agreed in one key respect: as Croll noted, '*the geological agents are chiefly the ordinary climatic agents. Consequently, the main principles of geology must be the laws of the climatic agents, or some logical deductions from them. It therefore follows that, in order to [pursue] a purely scientific geology,* ***the grand problem must be one of geological climate*** *[my emphasis]. It is through geological climate that we can hope to arrive ultimately at principles which will afford a rational explanation of the multifarious facts which have been accumulating during the past century.*'[7] Where the two men differed was in emphasis, Lyell stressing the pre-eminence of geography, and Croll that the existence of warm interglacial periods goes '*to prove that the long epoch known as the Glacial was not one of continuous cold, but consisted of a succession of cold and warm periods [which] is utterly inexplicable on every issue of the cause of the glacial epoch which has hitherto been advanced*'[7].

Lyell was concerned enough about Croll's astronomical challenge to his geographical theory of climate change that he wrote to Herschel and the Astronomer Royal, Sir George Biddell Airey. This correspondence led him tentatively to accept Croll's theory as a minor cause of climate change[6]. He must have felt he had an edge over Croll in that Croll had concluded that, following his theory, ice ages should have recurred through time. It did not disturb Croll that no evidence for them had been found in the warmer Tertiary; after all, the inadequacy of the geological record could well explain their absence[7]. Lyell disagreed, considering that eccentricity alone could not be the cause of the post-Pliocene ice ages, because there was no evidence for ice ages in the Tertiary or the Cretaceous formations, or indeed back to the Carboniferous[11]. '*This absence of recurrent periods of cold is perfectly explicable*', he went on, '*if I am right in concluding that they can only be brought about by an abnormal quantity of land in high latitudes*'[11].

While we might think this a stubborn adherence to what might be becoming an outdated idea, Lyell regarded the geographical principle of climate change as one of his major contributions to the science of geology, and it is hard to let go of your favourite ideas, especially when compelling evidence for the competing theory is weak or absent. Besides, we now know that they may both have been right: land in the polar regions does help to build up substantial accumulations of ice, in accordance with Lyell's view, and Earth's orbital changes do modify the climate, in accordance with Croll's, although not to the extent of forming glaciations in warm periods like the early Tertiary and Cretaceous, as Croll thought. That is where greenhouse gases come in, as we shall see later. Neither man considered them.

Croll's work influenced many eminent scientists, including Lyell, Darwin and James Geikie[6, 13]. Darwin was more forthcoming than Lyell in his praise for Croll's theory, '*in part because it provided a valuable mechanism for speciation*'[6]. He wrote to Croll on 24 November 1868 that '*I have never, I think, in my life, been so deeply interested by any geological discussion*', agreeing with Croll that the advocates of the iceberg theory (such as Lyell) had formed '*too extravagant notions regarding the potency of floating ice as a striating agent*'[6] and that '*scored rocks throughout the more level parts of the United States result from true glacier action*'[14].

3.4 Croll Defends his Position

Croll realised that one barrier to getting his astronomical theory accepted was that scientists tend to find what they are looking for[7]. Before publication of his astronomical theory in 1864, there was no impetus to seek evidence for interglacial periods. That the evidence existed, he was sure, recalling reading some years previously a paper describing fossiliferous sediments found between deposits of glacial till, which contained '*rootlets and stems of trees, nuts, and other remains showing that it had evidently been an old interglacial land surface.*'[7] After 1864, evidence for interglacial deposits began to emerge[13], including evidence that warm interglacial conditions had extended as far north as 75° 32' N in the Arctic[7]. While Croll took these data on board[7], Lyell largely ignored in his last edition of 1875[11] the detailed findings on glacial and interglacial geology that James Geike began publishing in 1874[13]. By then, Lyell was at the end of his life. From 1875 on, Croll and Geikie carried the day, their major opponent having vanished from the scene.

Unfortunately for the astronomical theorists, while orbital variations could be calculated fairly accurately, 19th-century geologists could date rocks only crudely. It was impossible to precisely relate sedimentary sequences to astronomical variables, or to test Croll's notion that glaciations alternated between the hemispheres. All that Croll could do was use rates of erosion and deposition to suggest that the glacial epoch ended around 80 Ka ago[7]. In fact, it ended around 20 Ka ago, but this was a good best guess for those times.

James Geikie supported Croll's theory, with the caveat that '*it must be confessed that a complete solution of the [Pleistocene Ice Age] problem has not yet been found*'[13]. He realised that Lyell's requirement for land in the polar regions to explain glaciations did not address the real issue: the complex alternation of cold and warm epochs. It was unreasonable to suppose that land moved in and out of the polar regions sufficiently rapidly to explain the origin of glacial to interglacial cycles. Lyell had also called on increases in the elevation of land to explain the origin of cold periods. Geikie took issue with that too, considering it unlikely that highlands had popped up and down fast enough to account for the observed cycles[13].

Croll's work was widely discussed but generally disregarded, not least because of geologists' continuing inability to date variations at a fine enough scale. By the time Croll died, geologists realised that glacial conditions had persisted much later than his proposed peak glaciation

80 Ka ago, and many thought his theory must be wrong. James Geikie hoped that '*some modification of his views will eventually clear up the mystery. But for the present we must be content to work and wait*'[13]. Advances in the theory and in dating rocks were needed to revive his work.

3.5 Even More Ancient Ice Ages

Agassiz's discovery changed the way field geologists thought about the rocks they saw. One of the first to respond, in 1855, was Professor Andrew Constable Ramsay (1814–1891), another of those Scottish geological fellows of the illustrious Royal Society of London. He was president of the Geological Society of London, and in 1872 became director-general of the Geological Survey of Britain. He was awarded the Wollaston Medal of the Geological Society in 1871 and the Royal Medal of the Royal Society in 1880, and was knighted in 1881.

Ramsay had a special interest in the effects produced by ice, and applied it to interpreting the origin of the Permian breccias skirting the English and Welsh coal fields. The breccias comprise many large, polished and striated angular fragments of rock stuck in a '*marly paste*'[15]. He deduced '*that they are chiefly formed of the moraine matter of glaciers, drifted and scattered in the Permian sea by the agency of icebergs*'. The Permian strata overlie the older Carboniferous coal measures, in which the coal was assumed to be the remains of swamps and forests growing in '*a moist, equable, and temperate climate, possibly such as that of New Zealand*'[15]. Croll was delighted to see evidence for a major glaciation far earlier in time than the relatively recent Ice Age, because it supported his notion that regular changes in the Earth's orbit should have led to glaciations in the distant past[5] and meant that Earth's climate could not be explained simply in terms of a gradual cooling.

By the time he wrote his extensive work on climate and time[7], Croll knew that the great coal formations of the Carboniferous Period had been deposited in cycles, with thin coal beds made from the remains of forests formed on land alternating with thin beds of marine clay, suggesting a succession of geologically rapid changes from a terrestrial to a marine environment and back. Croll interpreted this succession as possibly representing repeated changes from warm interglacial periods, when the sea level was low and coal forests grew, to cold glacial periods, when the sea level was high and marine clays were deposited. Although alternations between warm and cold conditions were consistent with his astronomical theory, he missed the point that during cold glacial conditions the sea level should have been low rather than high, with more water being trapped in ice at those times. We will explore the origin of cyclical deposits of the Carboniferous more in Chapter 6.

3.6 Not Everyone Agrees

By the end of the 19th century, a lot more was known about how the modern climate system worked than when Lyell first set down his *Principles*. Other geologists had begun to write treatises about the climates of the geological past. One was the Dutch palaeo-anthropologist and geologist Marie Eugène François Thomas Dubois (1858–1940) (Box 3.2), famed for discovering 'Java Man' (*Pithecanthropus erectus*, later named *Homo erectus*).

Box 3.2 Marie Eugène François Thomas Dubois.

Raised in Eijsden in Limburg, The Netherlands, Dubois was fascinated by natural history. He studied medicine at the University of Amsterdam, obtaining his degree in 1844. Specialising in comparative anatomy, he developed an interest in human evolution and the link between humans and apes. In 1887, he joined the Dutch army to get himself posted to the Dutch East Indies – now Indonesia – because he felt sure that the 'missing link' between apes and humans lay in the tropics. There, he searched caves on Sumatra and Java, finding 'Java Man' in 1891. He returned to Europe in 1895 and was awarded an honorary doctorate by the University of Amsterdam in 1897, becoming professor of geology there in 1899. He also served from 1897 to 1928 as keeper of palaeontology, geology and mineralogy at Teyler's Museum in Haarlem.

Aside from his fascination with the link between humans and apes, Dubois was intrigued by the climatic changes of the past, publishing an expanded essay on this topic in 1895[16]. His article brought to an English-speaking audience a wide range of references to the growing understanding of past climate change, especially in Germany. Notable among these was the work of Melchior Neumayer (1845–1890)[17], who had shown the biogeographical link between Brazil and Africa across the South Atlantic, and that of Swiss geologist and naturalist Oswald Heer (1809–1883)[18–20], whom Dubois considered to be the 'father of palaeoclimatology', noting that, '*To him we owe nearly all the information which we possess about ancient climates*'[16]. Heer was Professor of Botany at the University of Zurich. For his services to science, the Geological Society of London awarded him its Wollaston Medal in 1874.

Dubois drew attention to the growing evidence from fossil plants and animals that the climate of the Arctic had declined from almost tropical in the early Tertiary to the cold conditions of today. There was ample evidence from the early Tertiary and former times – especially the Jurassic and the Cretaceous – that, while they had been warmer than today, their heat had been distributed in climate zones between the Equator and the pole as they presently exist. No displacement of the poles seemed necessary to explain the distribution of these zones. That appeared to knock on the head, at least temporarily, Lyell's theory of continental displacement as a cause of climate change. For earlier times, such as the Permo-Carboniferous, where there was evidence for the action of ice far from the present poles, Dubois preferred to explain their occurrence as caused by increased precipitation rather than by excessive cold, citing as an example the occurrence of glaciers in temperate New Zealand today.

How, then, could the Cenozoic cooling be explained? Dubois believed that the answer must lie with the energy emitted by the Sun, which must have declined with time, but he also recognised that ocean currents play an important role in transporting heat away from the tropics. He thought that periodic changes in the Sun's output, like those causing the sunspot cycle, might explain the warm interglacial periods of the Ice Age. While the astronomical variations called upon by James Croll might explain some of that variation in Pleistocene times, they were inadequate to explain the general cooling of the Earth in Cenozoic times. '*It now seems to be completely proved*' said Dubois '*that no other source of heat than the sun can ever have exercised an appreciable influence either on the meteorological condition of the Earth, or on the climates. To any very considerable changes of the solar heat we must, therefore, look for the cause of the geological changes of climate*'[16].

Dubois can perhaps be taken as typical of the geologists of the time. He was unaware of the effects of greenhouse gases in modifying the Sun's heat and neglected the possibility that the continents might have changed their positions with relation to the poles and to each other. Breakthroughs in the sciences would be needed before the prevailing paradigm could change. We turn in the next chapter to the efforts of 19th-century scientists to explore the possibility that changes in the Earth's climate resulted from changes in the composition of the atmosphere.

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